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MULTI-TeV MUON COLLIDERS*

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ABSTRACT

The possibility that muons may be used in a future generation of high-energy high-luminosity $\mu^+ \mu^-$ and μ-p colliders is presented. The problem of collecting and cooling high-intensity muon bunches is discussed and ionization cooling is described. High-energy collider scenarios are outlined; muon colliders may become superior to electron colliders in the multi-TeV energy range.

INTRODUCTION

Progress in the understanding of elementary particle physics has required continuing increases in accelerated beam energies. Currently, the highest energy colliders are proton-(anti) proton (p-$\bar{p}$ or p-p) and electron-positron machines, and both approaches have significant difficulties in the extension to higher energies.

Protons are composite objects, so only a small fraction of the total energy participates in a collision; this fraction decreases as energy increases. Also, production of new particle states is masked by a large background of nonresonant events; identification of new physics becomes increasingly difficult with increasing energy. The e^+–e^- collisions have had the advantage of providing simple, single-particle interactions with little background, and e^+–e^- storage rings have been the principal tool in the exploration of high-energy resonances (Ψ, Υ, Z_o). However, synchrotron radiation causes energy loss according to

$$\frac{\Delta E}{turn} = \frac{4\pi e^2}{3R}\left(\frac{E}{mc^2}\right)^4, \tag{1}$$

where E,e and m are the particle energy, charge, and mass, and R is the ring radius, and this energy loss prevents extension of e^+–e^- storage rings beyond $E \cong 100$ GeV/ particle. Linear colliders ($R \to \infty$) may reach higher energies; but at very high energies (many TeV), they are severely limited in luminosity and energy resolution by beamstrahlung, radiation during collisions, and face great challenges in obtaining adequate luminosity at reasonable cost.

In this paper, we describe an alternate approach that retains the high-quality features of e^+–e^- colliders. By accelerating and colliding higher mass leptons such as muons, the advantages of e^+–e^- colliders can be extended into a higher energy regime (1 TeV $\to$ many PeV). The physical interactions of muons are believed to be the same as electrons with one difference: the direct muon coupling into the Higgs sector is a factor $(m_\mu/m_e)^2$ larger.

The principal liabilities of muons are their short lifetimes and the large phase-space area of initial muon beams produced in π-decay. However, the lifetime τ, given by

$$\tau = 2.197 \times 10^{-6} \frac{E_\mu}{m_\mu}\, s\,,$$

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increases linearly with energy and is adequate for linacs and at $E_{max} \lesssim 1$ TeV is adequate for rapid cycling synchrotron colliders.[1,2] Also, the phase-space density of muons is substantially increased by adiabatic damping in acceleration to high energy and can be increased by ionization cooling[3,4] at source energies. These damping processes can increase muon beam densities to levels where high-luminosity $\mu^+\mu^-$ and μ^-p colliders may be possible.

MUON PRODUCTION, COLLECTION, AND COOLING

Production of large numbers of muons is not difficult in principle. Hadronic interactions are characterized by the production of large numbers of pions; almost all of these pions decay into a muon plus a neutrino. The collection of these muons is somewhat more difficult, because pions are produced over a broad energy range with transverse energies of the order of the pion mass, and π decays produce muons over a large energy spectrum with transverse energies less than the pion muon mass difference.

The problem of pion production and collection is similar to the current problem of $\bar{p}$ collection; therefore, in a first approximation, a similar device is suggested.[5] A high-intensity proton beam is focused onto a high-density target, and the target is followed by a collector lens system that confines the pions into a transport channel for injection into $\mu^\pm$ collector rings. The π decay in the transport channel or in the collector provides muons that can be stored and cooled. The difficult problem of optimizing the μ collector for maximum intensity is not addressed in this paper; however, some guidelines for solving the problem are suggested. A first estimate of $\pi^\pm$ production in proton-hadron collisions may be obtained using the empirical formulas of Wang:[6]

$$\frac{d^2N}{dPd\Omega} = AP_mX(1-X)\exp(-BX^C - DP_t)\left[\frac{\text{pions}}{\text{sr(GeV/c)}}/\text{interacting proton}\right], \qquad (2)$$

where $P_m = P_{proton}$ is the maximum allowed pion momentum, X is the pion/proton momentum ratio, P_t is the pion transverse momentum, and $A = 2.385$ (1.572), $B = 3.558$ (5.732), $C = 1.333$ (1.333), and $D = 4.727$ (4.247) for positive (negative) pions. If we assume, extrapolating from $\bar{p}$ channels, that the acceptance of ~ 1 GeV pions in the decay transport channel is of order 200 mrad and $\pm 20\%$ in momentum, then $\sim 0.1\ \pi^\pm$/per primary high-energy proton may be collected. This estimate may be somewhat optimistic in the transport acceptance; however, it only includes π's produced from primary proton-proton collisions. Secondary collisions may produce substantially more π's, particularly if the primary proton energy is much greater than 1 GeV. Also, experimental evidence indicates that the Wang formulas may underestimate π production in that regime.[7] If the momentum acceptances of the $\mu^\pm$ collectors are $\sim \pm 10\%$ with adequate transverse acceptance, then $\gtrsim 10\%$ of these π's may produce stored muons. The $\mu^\pm$ source will require strong focusing to obtain a μ beam with a minimum initial emittance ($\sim 100\ \pi$ mm-mrad).

There are many unsolved problems in developing an optimum system. The optimum proton energy for $\pi^\pm$ production is not known. Wang predicts π production independent of proton energy for $E_p \gg E_\pi$; experimental evidence shows production proportional to E_p.[7] The π collection should also include production in secondary interactions and hadronic cascades. We expect that $E_p \approx 30$-100 GeV for $E_\pi \approx 1$ GeV may be an economic optimum.

Also, μ collection from π decay presents significant design challenges. A solution may include multiturn π decay in a straight section of a collector ring in which only the decay product muons are in circulating orbits (stochastic injection).[5]

As the principles of muon cooling have been described elsewhere,[1-4] we summarize some of the basic concepts. The process is similar to radiation damping in electron storage rings with energy loss in material absorbers replacing synchrotron radiation. The basic mechanism of μ cooling is displayed in Fig. 1. The muon beam passes through a material medium, in which it loses energy, followed by an accelerating cavity, where it regains the average longitudinal energy loss. Energy cooling occurs following

$$\frac{d(\Delta E_\mu)}{dn} = -\frac{\partial \Delta_\mu}{\partial E_\mu} \Delta E\mu \,, \tag{3}$$

where ΔE_μ is the muon energy deviation from the central value, Δ_μ is the energy loss, and n is the cycle number. Transverse cooling occurs because energy loss is parallel to the particle trajectory and has a transverse component, but energy regain is purely longitudinal. Expressing this in emittances, we obtain

$$\frac{d\epsilon_\perp}{dn} = -\frac{\Delta_\mu}{E_\mu}\epsilon_\perp \tag{4}$$

for both transverse degrees of freedom.

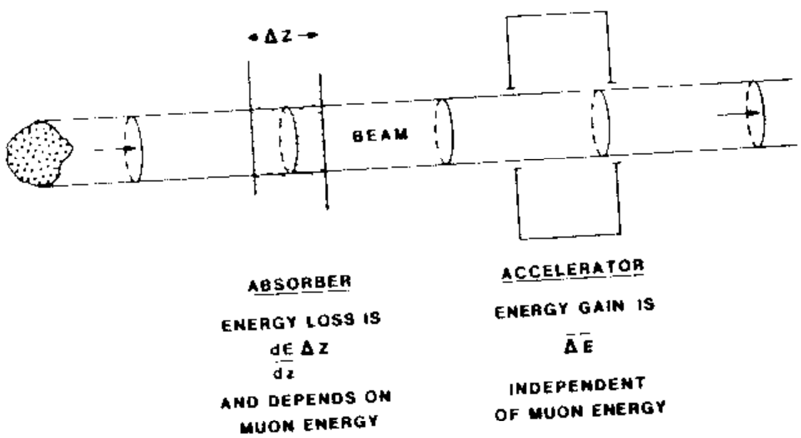

Fig. 1. Sketch of "ionization cooling" principle.

Longitudinal cooling depends on

$$\frac{\partial \Delta_\mu}{\partial E_\mu} \,,$$

which is naturally slightly positive for $E_\mu \gtrsim 0.3$ GeV but is steeply negative for low-energy muons. This implies that cooling requires $E\mu \gtrsim 0.3$ GeV. This slow cooling can be enhanced by placing a wedge-shaped absorber in a dispersion region, where position is energy-dependent (see Fig. 2).[1] The sum of transverse and longitudinal cooling rates is invariant.

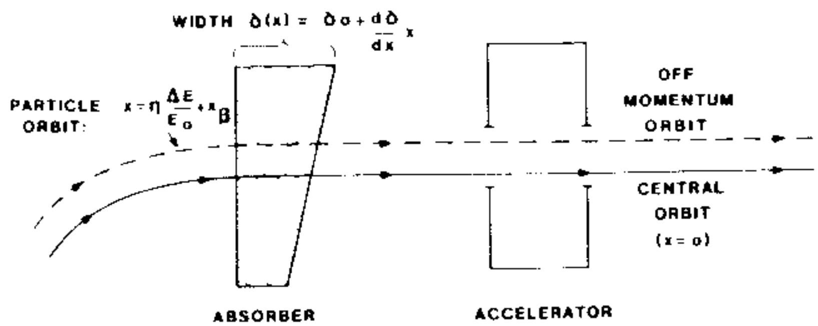

Fig. 2. Use of wedge absorber to enhance energy dependence of energy loss.

Muon cooling is limited by heating caused by statistical fluctuations in the number and energy of muon-atom interactions. The resulting equation for energy cooling is

$$\frac{d}{dn} \langle (\Delta E)^2 \rangle \cong -2 \left(\frac{\partial \Delta_\mu}{\partial E_\mu} \right)_{total} \langle (\Delta E)^2 \rangle + \Delta_\mu I \ . \tag{5}$$

where I is the mean energy exchange (~10Z eV). The equation for transverse cooling is

$$\frac{d\epsilon_\perp}{dn} \cong -\frac{\alpha \Delta_\mu}{E_\mu} \epsilon_\perp + \frac{\beta_\perp}{2} \Theta^2_{rms} \ , \tag{6}$$

where α is a correction factor for enhanced momentum cooling and Θ_{rms} is the mean scattering angle in the absorber. This equation places a premium on low $\beta_\perp$ (strong focusing) at the absorber. This constraint may imply that an optimum absorber would be an active focusing element (Li lens), which also has relatively small scattering.

Muon cooling may be used in either storage rings or linacs. A sample cooling ring is displayed in Fig. 3. showing focusing sections for absorbers and acceleration sections. Several stages may be used to obtain optimum cooling. Reference 1 outlines a two-stage system that reduces transverse emittances of 1 GeV muons by a factor of 100 to $\lesssim$2 mm-mrad, accompanied by similar decreases in longitudinal phase space.

The important constraint is that cooling be completed within a muon lifetime, which can be expressed as ~300 $\bar{B}$(T) turns in a storage ring, where $\bar{B}$ is the mean bending field, or as a length $L_\mu \approx 660\, E_\mu/m_\mu$ meters of path length in a linac. This constraint is not insurmountable.

APPLICATIONS OF COOLED MUONS IN HIGH-ENERGY ACCELERATORS

Cooled muons have many possible uses in high-energy accelerators. In this section, we emphasize applications not readily accessible to $e^\pm$ machines, such as colliders at $\gtrsim$ 1 TeV energies.

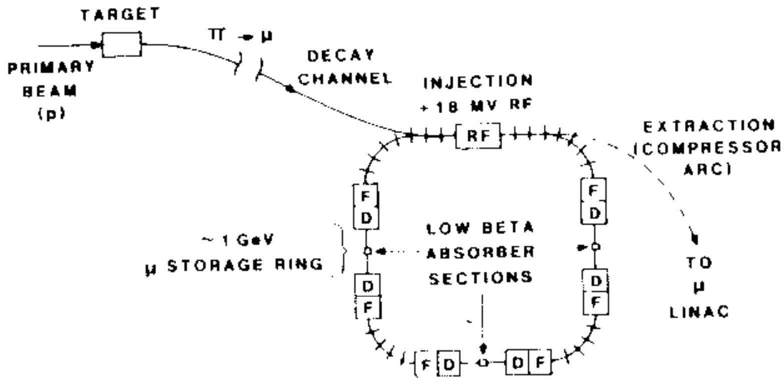

Fig. 3. A muon cooling ring.

The μ^+-μ^- Rapid-Cycling Collider

Most collider applications will require a high-intensity muon source operating at a frequency f greater than the inverse of the muon lifetime. At $E_\mu = 1$ TeV, $\tau_\mu \approx 0.02$s, so a rapid-cycling synchrotron operating at $f \gtrsim 60$ Hz is adequately matched to that lifetime.

In Fig. 4, we display the major components of a 1-TeV μ collider: a rapid-cycling proton synchrotron with a target to produce π's, a decay channel (or stochastic injection[5] into a collector ring) for $\pi \to \mu\nu$ decay, a storage-ring/linac system for μ cooling, and a μ linac for injection into a rapid-cycling synchrotron with its period matched to the protron synchrotron.

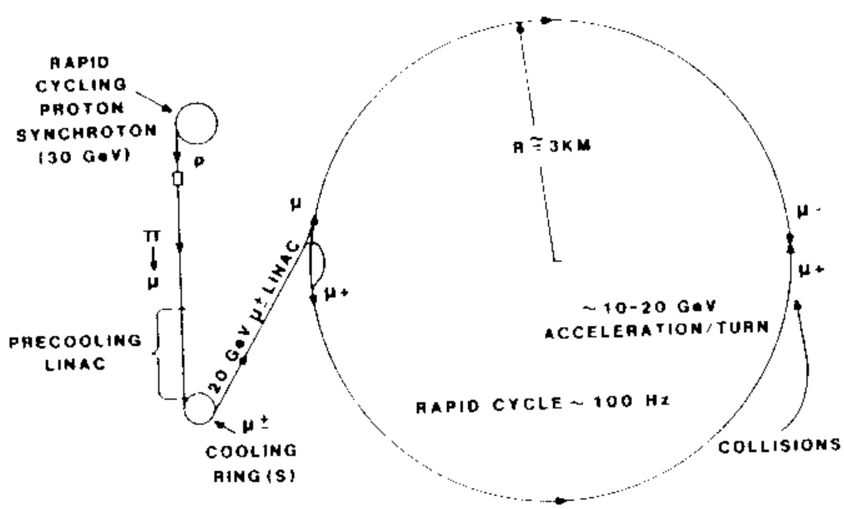

Fig. 4. The ~1-TeV μ rapid-cycling synchrotron collider

The μ^+-μ^- collider luminosity L may be estimated using

$$L = \frac{f_c \, n_T \, n_B \, N^+ N^-}{4\pi\beta^*\epsilon^*} \tag{7}$$

With 10^{14} primary protons per pulse and muon collection efficiency of 10^{-2}, we obtain 10^{12} stored $\mu^\pm$, which may be organized into $n_B = 4$ bunches with $N^+ = N^- = 2.5 \times 10^{11}$ per bunch. The cycling frequency f_c is 30 Hz, n_T is the mean number of turns of beam storage ($n_T \approx 300$), and we use $\beta^* = 1$ cm and $\epsilon^* = 2 \times 10^{-7}$ cm R to obtain $L \approx 10^{33}$ cm^{-2} s^{-1} for a 1-TeV μ^+-μ^- collider.

The obtainable luminosity is expected to increase with increasing energy as the muon lifetime increases and the beam emittance and momentum spread are adiabatically damped. The factor ϵ^* will decrease as 1/E, and β^* can also decrease as 1/E, if the focusing is limited by peak field and lens length as a fraction of circumference. The cycling frequency f_c decreases as 1/E as the lifetime increases, and n_T can increase since B, the mean bending field, can be increased as the cycling frequency decreases. As the muon lifetime increases, successive cycles of the rapid-cycling proton synchrotron can be accumulated in a proton collector (or collectors) for pulsed bursts matched to the muon lifetime. In this mode, both N^+ and N^- increase proportionally to E. Collecting these factors together, we find that luminosity should increase as E^3. This scaling should be valid up to ~100 TeV (where radiation damping may be used to further reduce emittances). At energies $\gtrsim$ 1000 TeV, radiation excludes storage ring colliders and μ^+-μ^- colliding linacs are preferred.

The μ^+-μ^- Linac-Injected Storage-Ring Collider or Linear Collider

If the present research effort is successful in developing economical, high-gradient linacs, they may be used to accelerate muons in linear colliders[3] or in a linac storage-ring scenario. The linac injected storage-ring is displayed in Fig. 5. Separate μ^+ and μ^- bunches are accelerated in the linac to full energy and then injected in opposite directions in a superconducting storage ring for multiturn collisions. Luminosity can, in principle, be much higher than in the rapid-cycling synchrotron ($L \gtrsim 10^{33}$) because beam loss in acceleration is greatly reduced and stronger bending field increases n_T and decreases β^* in Eq. (7).

The μ-p Collider

An important advantage of of μ^+-μ^- colliders over e^+-e^- scenarios is that the same collider may also be used for μ^--p collisions with both beams at full energy. Reference 2 describes a technique for μ-p frequency matching. High luminosity is relatively easily obtained because only one beam (μ^-) is unstable. This is a probable initial operating mode for a circular μ^+-μ^- collider. Dedicated μ-p colliders are also possible.

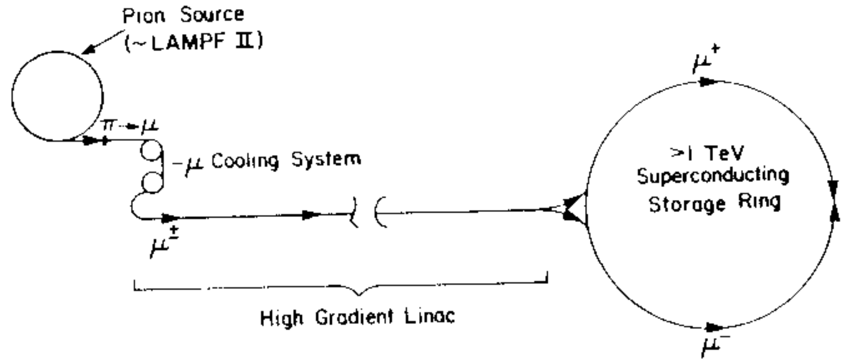

Fig. 5. The μ linac/storage-ring system.

FUTURE PROSPECTS

The μ^+-μ^- (or μ^--p) colliders have so far received only initial conceptual development and require considerably more research before implementation. More detailed design studies could optimize and evaluate the possibilities more precisely; experimental development would also be required. Initial experiments could determine π production, evaluate collection systems and measure μ energy loss in material media. Further experiments could then demonstrate the possibilities and limitations of μ cooling, possibly using existing facilities ($\bar{p}$ collectors, low-energy proton storage rings) in parasitic or dedicated modes. A detailed comparison with other collider possibilities (e^+-e^-, $p\bar{p}$, etc.) would then be required. The enhanced coupling of μ's to the Higgs sector may help make the muon collider an attractive candidate in a future generation of colliders.

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